

IR Diagnostics for Dynamic Failure of Materials



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This project is exploratory research into the thermodynamics of dynamic deformation and failure of materials, using high-speed and spatially-resolved infrared (IR) temperature measurements. During deformation, mechanical work is converted to different forms of energy depending on the deformation process. For example, it can be dissipated as heat in purely plastic deformation, stored as strain energy in dislocations in metals and in oriented polymeric molecular structures, and expended during the generation of new surfaces during damage and fracture. How this work is converted into these various forms is not well understood. In fact, there is controversy for the relatively

simple case regarding the amount of work dissipated as heat during uniform plastic deformation.

Project Goals

The goals are to develop dynamic IR temperature measurement techniques and apply them to gain a better understanding of the dynamic failure processes in both metals and polymeric composite materials. The experimental results will be compared against predictions of existing constitutive models and guide the development of higher fidelity models if needed.

Relevance to LLNL Mission

The completion of this project will improve our competency in stockpile stewardship materials experiments. Future DOE applications of the IR temperature measurement technology include machining and safety aspects of explosives, verification of existing material models, and contributions to the development of new material models. The capabilities will be immediately applicable to the study of hazardous (radioactive, toxic, and explosive) materials that are unique to NNSA laboratories. The capability will also be beneficial to DoD for armor/anti-armor applications of materials; and to NNSA for penetrator case materials in the Robust Nuclear Earth Penetrator program, and for materials for explosive containment vessels.

FY2004 Accomplishments and Results

To resolve the controversy regarding the percentage of plastic work that is converted to heat for metals, we have completed a series of experiments.

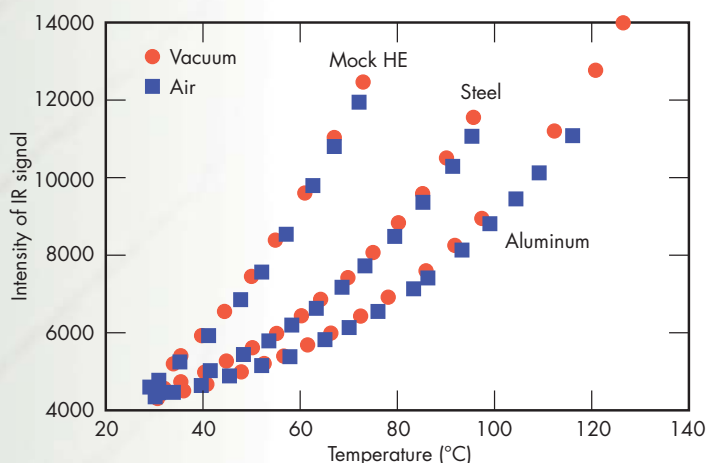


Figure 1. Comparison of IR temperature calibrations in air and vacuum for various materials.

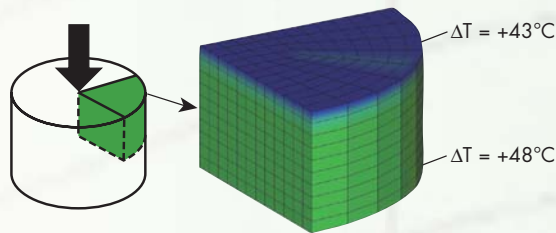


Figure 2. Spatial distribution of temperature rise in a top quadrant of a cylindrical metal specimen that is uniformly compressed to a true strain of 35% at a rate of 35 s^{-1} .

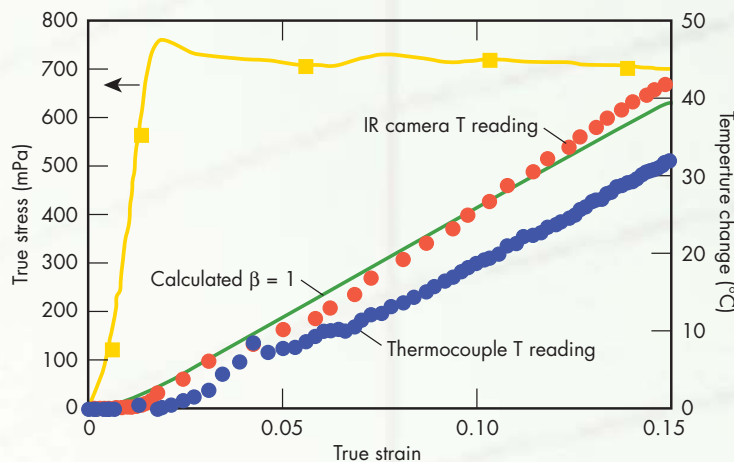


Figure 3. Stress-strain response and simultaneous temperature measurement during compression of pure Ta at a strain rate of 10 s^{-1} .

Calibrations of IR temperature measurement in controlled environments were performed using an environment chamber designed for this purpose and for controlling atmosphere during dynamic deformation. We have shown that there is no significant difference between calibrations performed in air or vacuum for metals and a mock high explosive (HE) (Fig. 1).

Repeated calibrations in air of both metals and mock HE to maximum temperatures expected during dynamic deformation ($\sim 100^\circ\text{C}$ above ambient) showed that emissivity did not change. This demonstrates that for these materials, surface oxidation does not occur or does not alter IR emissivity in this temperature range.

Thermomechanical modeling using LS DYNA was performed for the uniform

compression of metals at different strain rates to determine when adiabatic conditions are met. At intermediate strain rates ($\sim 10 \text{ s}^{-1}$) most of the specimen is compressed adiabatically (Fig. 2).

Preliminary tests with Ta at intermediate strain rate yielded different values of temperature when measured using IR and a thermocouple. An example is shown in Fig. 3, where the Taylor-Quinney coefficient, β , which represents the fractional conversion of plastic work heat, is found to be 1.0 for IR measured temperature and 0.8 for thermocouple data. We are characterizing the emissivity of deformed specimens and the temperature response of the thermocouple on the specimen to resolve this discrepancy.

FY2005 Proposed Work

If we find that β is significantly less than 1—indicating that a significant fraction of work is stored as a change in internal energy—we will study how the remaining mechanical work is stored in a plastically deformed material. If β is found to be close to 1, we will have shown that plastic deformation is a completely dissipative process. We will also characterize the temperature gradients due to strain localization from shear bands in dynamic deformation experiments with metals using the high-speed detector acquired in FY2004. A key part of this work will be the measurement of the detector system spatial resolution in terms of a modulation transfer function determined using either line or edge broadening.

We will also continue the work with mock HE to determine the energy conversion and dissipation mechanisms under uniform dynamic deformation.